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Correlation analysis of inter-annual variability of IWR, precipitation and NDVI

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Synopsis

The SiBUC (Simple Biosphere including Urban Canopy) land surface scheme which has irrigation scheme is one of participants of the GSWP2 (the 2nd Global Soil Wetness Project). Accordingly, global 10-year simulation considering irrigation was implemented, and global distribution of IWR (Irrigation Water Requirement) was estimated. From the analysis of two correlation coefficients (cc1: between precipitation and IWR, cc2: between precipitation and NDVI), it was found that not only regions where cc1 is negative and cc2 is neutral but also regions where both cc1 and cc2 are positive exist. It can be implied that this difference of correlation expresses whether the irrigation facilities are adequate or not.

Keywords: SiBUC, correlation coefficient, irrigation water requirement, precipitation, NDVI

1. Introduction

The 21st century is often called ”the century of water”. The general concerns are increasingly focused on the change in the precipitation pattern owing to global warming, the global water problems such as floods or droughts, stable supply of water for agricultural and domestic use, and so on. As regards agricultural water use, it is estimated that agriculture receives 66 percent of total water withdrawal and 85 percent of consumption in the world (Shiklomanov et al., 2000). Irrigated agricultural land produces over 40 percent of world’s food (Doll and Siebert, 2002). Thus, the understanding of the global distribution of irrigation water requirement and its response to climate variability is fundamental for stable supply of water for agriculture and sustainable water management.

In this study, land surface scheme is applied in order to estimate the global distribution of irrigation water requirement. Particularly, the SiBUC (Simple Biosphere including Urban Canopy) model is utilized since it has the irrigation scheme for various kind of crops. In order to understand the characteristics of irrigation water requirement at each grid box, the inter-annual variability of irrigation water requirement, NDVI and precipitation are analyzed.

2. Land surface scheme (SiBUC)

2.1 Basic concept of SiBUC

In the atmospheric boundary layer, the radiative energy absorbed from the sun and the atmosphere is partitioned into fluxes of sensible, latent and ground. This surface flux partitioning (redistribution of absorbed energy) is strongly dependent on both the land cover characteristics and its hydrological state. Especially, heat budget characteristics of water body and urbanized area are much different from those of vegetation and soil surface. Thus, they may have significant effects even when their coverage areas are not so large. LSS should have a framework of treating the urbanized area, inland water. However, these kinds of land use are usually omitted in the existing LSSs without enough investigation about how they act in regional and global climate systems.

From such considerations, the SiB (Simple Bio-

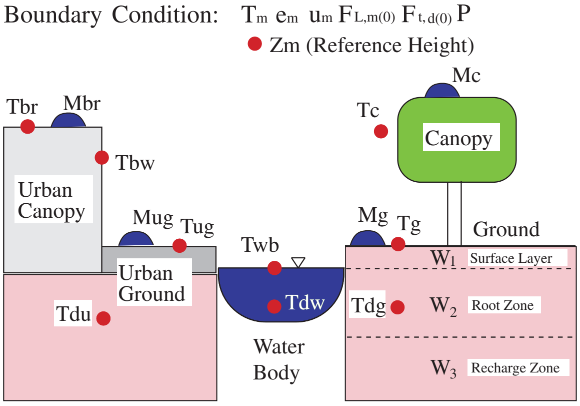


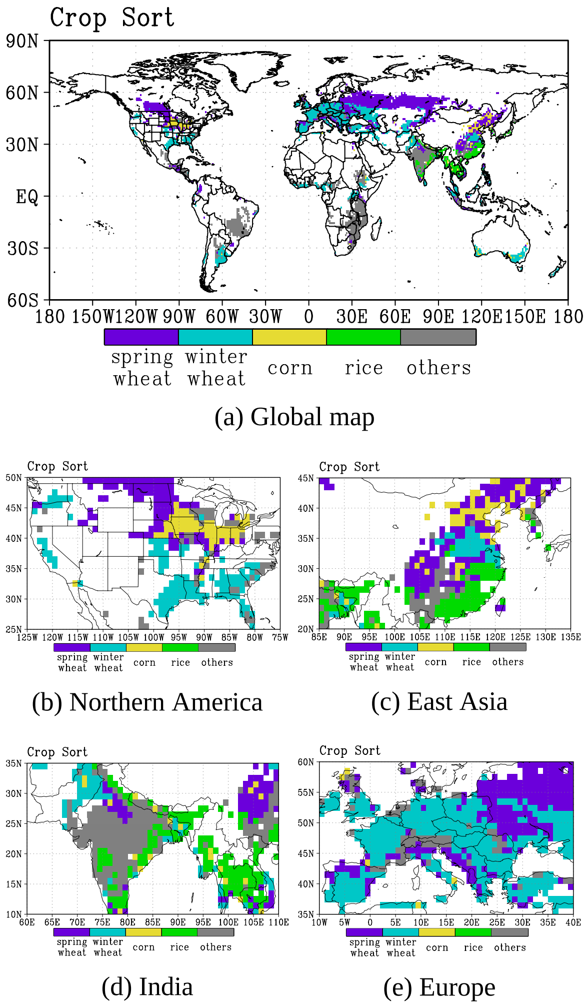
Fig. 1 Schematic image of surface elements and prognostic variables in SiBUC.

sphere) model (Sellers et al., 1986) was expanded to the SiBUC model. The SiBUC model has been developed at DPRI Kyoto University (Tanaka, 2004) and has three sub-models (green area, urban area, water body) for each grid box. SiBUC is aimed to describe the basin-scale land surface processes more realistically than existing models. Fig. 1 shows a schematic image of surface elements in SiBUC.

2.2 Irrigation Scheme

Most LSSs can be adapted for natural land surface area such as forest, grassland, bare soil and so on. However, the green area covers not only natural vegetation but also agricultural lands where irrigation should be considered. As is generally known, as one of the most representative land use in eastern and southeastern Asian Monsoon region, we have rice paddy field. There are obvious differences between rice paddy field and other cropland from the aspect of the energy and water budget. In the original version of green area model, that is SiB model, there is no framework to treat the rice paddy field (it is treated same as cropland).

Another motivation for the development of the irrigation scheme is to treat the irrigation water. In the irrigated rice paddy field, water is controlled / operated differently according to growing stage of rice. Thus, there is a need for describing the artificial water irrigation / drainage by farmer. Through the detailed analysis of the field data and the numerical simulation with green area model, it was found that the green area model is hard to be used for rice paddy field if the simulation period becomes longer. Therefore, a water layer, which has a temperature and depth is added



(a) Global map

(b) Northern America

(c) East Asia

(d) India

(e) Europe

Fig. 2 Global map of crop type with 1-degree spatial resolution.

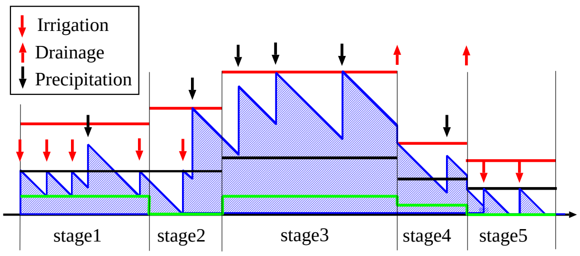
to the green area model to treat rice paddy field more accurately.

Basic concept of the irrigation scheme is to maintain water depth above the surface of green area within appropriate ranges that are defined for growing stage of rice. If some parameters for the irrigation scheme are defined, it is able to consider the irrigation in rice paddy field by the original green area model as well. The irrigation rules for rice paddy field are based on at least four parameters; planting date, harvesting date, the periods of each growing stage, and appropriate range of water depth for growing stage.

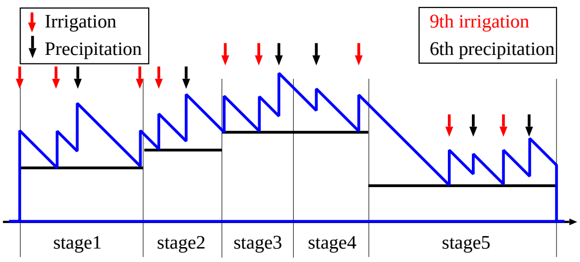
If soil wetness at root zone alternative to water depth is operated in farmland, the SiBUC model can be used for irrigated farmland. As well, the irrigation rules for farmland are planting date, harvesting date, the periods of each growing stage, and appropriate range of soil wetness at root zone for growing stage. These parameters are determined for each crop

Table 1 The period of each growing stage (Unit:%) and the low level of soil wetness at the root zone criteria for water depth (Unit:mm)

crop type	growing stage	1	2	3	4	5
spring wheat	period	23	14	14	14	35
	soil wetness	70	60	0	0	55
winter wheat	period	26	20	22	13	19
	soil wetness	70	70	0	0	55
corn	period		4	6	14	24
	soil wetness	75	65	70	75	65
soy bean	period	4	25	16	2	27
	soil wetness	75	65	65	70	65
rice	period	25	13	33	13	16
	minimum water depth	20	0	20	10	0
	optimal water depth	50	50	60	40	30
	maximum water depth	100	120	160	0	0



(a) rice paddy field



(b) farmland

Fig. 3 schematic image of maintenance of water depth in rice paddy field and soil wetness at root zone in farmland.

types, respectively.

2.3 Irrigation parameters

Yorozu et al. (2005) has made a global distribution of crop type (Fig. 2) and cropping calendar through the time series analysis of NDVI (Normalized Difference Vegetation Index). From these data set, agricultural lands are distinguished with five crop types; spring wheat, winter wheat, corn, rice, and others. And more, it is determined that total growing period in every crops consists of five growing stage, respectively. These dataset are closely related to Table 1. That table provides irrigation parameters about five crop types in China. In particular, that table shows the periods of each growing stage and lower soil wetness at the root zone or appropriate range of water depth for each growing stage.

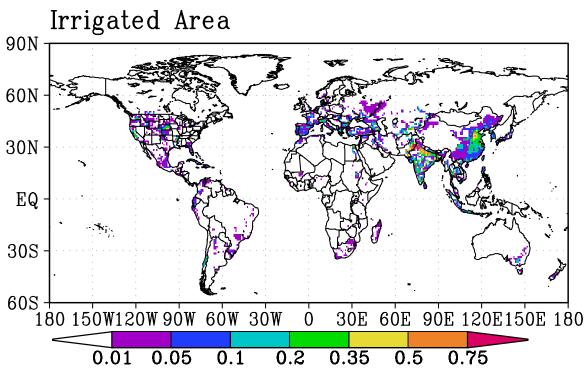


Fig. 4 The irrigated agricultural lands fraction with 1-degree spatial resolution.

During simulation, if soil wetness at root zone in farmland become lower than reference value given by the table, it is introduced that irrigation water requirement whose value is 5 mm, per irrigated area in grid box, which is not less than amount of water vapor by transpiration a day. In the case of rice paddy field, artificial water control is more complicated. If water depth in rice paddy field becomes lower than minimum water depth, water depth corresponds to optimal water depth as a result of introducing irrigation water requirement. If water depth becomes higher than maximum water depth, water depth corresponds to optimal water depth by drainage. Fig. 3 helps to understand these kinds of artificial water control.

This introduced water is defined as ”irrigation water requirement”. Irrigation water requirement means amount of water that must be applied to the crop by irrigation for optimal crop growth.

3. Application to global scale

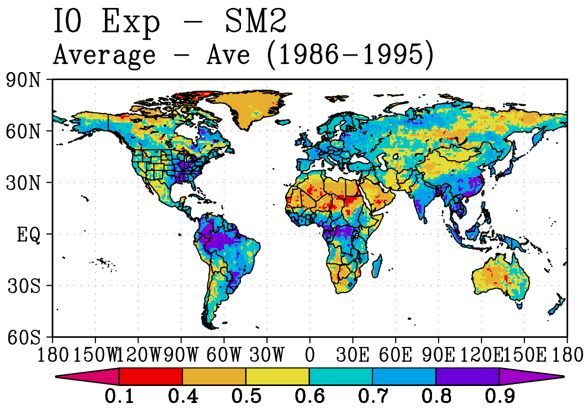
3.1 Global soil wetness project

Global Soil Wetness Project (GSWP) is open to anyone with a unique Land Surface Scheme (LSS) and an interest in participating. All participants run their LSSs with the provided forcing and boundary conditions, and provide the results of this ”baseline” integration. One of the most important goal of GSWP is to produce state-of-the-art global data sets of land surface fluxes, state variables and related hydrological quantities for 10-year period (1986-1995). Currently, there exists no global-wide capacity to directly measure the fluxes of water and energy over the continental surfaces, and thus we must rely on the highest-quality estimates based on model simulations. The GSWP-2 outputs will be combined with global precipitation products and ocean flux estimates to assess our scientific accounting of the global water cycle and to update our current depiction of the global energy cycle (Dirmeyer et al. 2002).

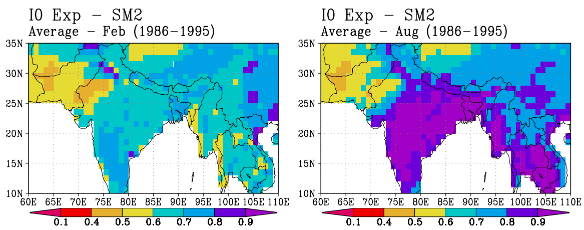
The SiBUC model is one of the participants of the GSWP. It uses mosaic approach to incorporate all kind of land use into LSS. The baseline simulation of GSWP2 pays no attention to the irrigation effect. However, not a small part of the world’s cropland is irrigated as Fig. 4 shows an global map of irrigated agricultural lands fraction. In order to estimate global soil wetness field as accurately as possible, SiBUC is run with irrigation scheme activated to consider this effect.

3.2 Simulation design

The domain of simulations in this research covers the whole world. The integration time is 10 years from 0000UTC 1 Jan 1986 to 0000UTC 1 Jan 1996 at a spatial resolution of 1 degree and time step of Δ 1 hour is used.

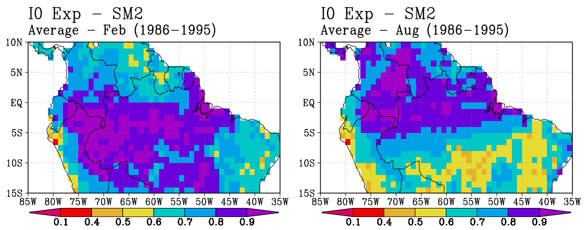


(a) Annual average of global distribution



February August

(b) India



February August

(c) Northern region of South America

Fig. 5 A distribution of soil wetness at root zone, whose value shows average for 10 year by I0 exp.

All input data set for model are specified from the ISLSCP (International Satellite Land-Surface Climatology Project) initiative II data set (Hall et al. 2004).

The SiBUC is integrated from 0300UTC 1 July 1982 because of implementation of spin-up process for the 3.5-year period. The conditions of spin-up at beginning are soil wetness at 75% of saturation, no snow cover and specified soil temperature (provided). As a result of spin-up, the initial conditions of the evaluation period are calculated. Then, the SiBUC is integrated globally for the 10-year period 1986-1995.

In this paper, the simulation, which is considering irrigation effect is called as I0 exp and the baseline

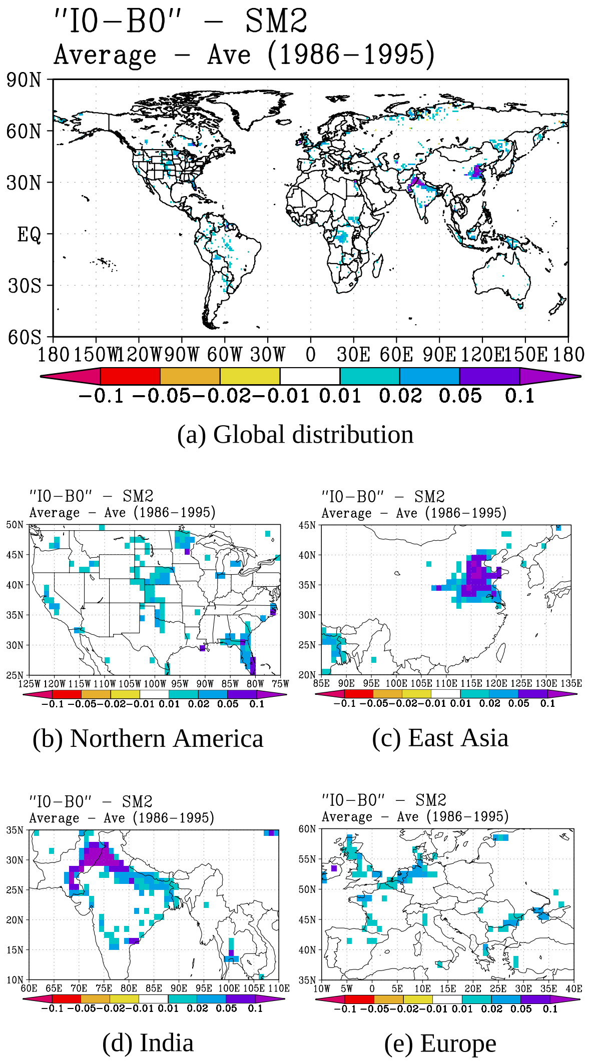


Fig. 6 The 10 years averaged distibutional difference of soil wetness at root zone between B0 exp and I0 exp.

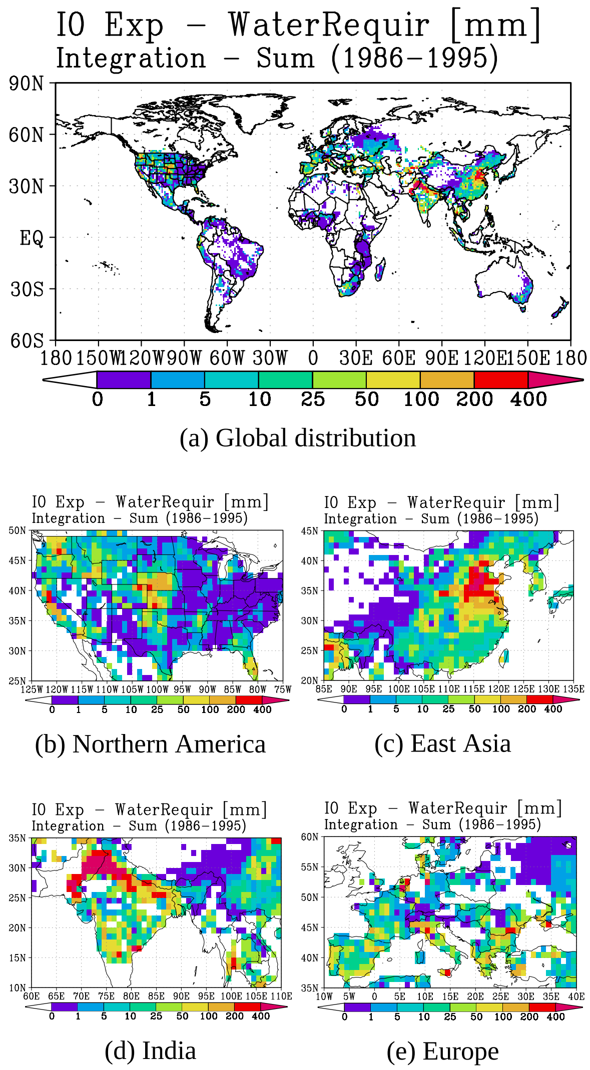


Fig. 7 A distribution of irrigation water requirement, whose value shows average for 10 year by I0 exp.

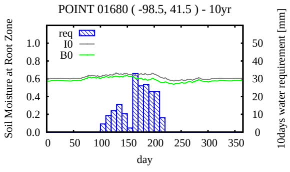
simulation (NOT considering irrigation effect) is called as B0 exp.

3.3 Effects of irrigation

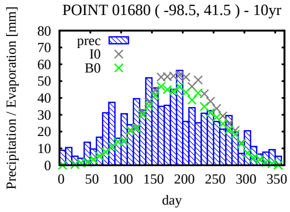
The average for 10 years distribution of soil wetness at root zone estimated on I0 exp is shown in Fig. 5. From Fig. 5 (a), in the arid desert region which spreads over the Middle East, the northern Africa and the western Australia, soil wetness value was estimated between 0.3 and 0.5. In the rainfall forest around the equator, the soil wetness value shows over 0.8. It can be seen from Fig. 5 (b) that the SiBUC model succeeds in expressing the variation of soil wetness between in dry season and in wet season. Moreover, movement of the moist area in the northern region of South America can be expressed (See Fig. 5 (c)). From a point of view described above, roughly speaking the global distribution of soil wetness estimated by SiBUC model does express the differences between dry area and wet area.

Fig. 6 shows differences of soil wetness at root zone between B0 exp and I0 exp. There is a significant increase of soil wetness at root zone because of irrigation. The 10-year averaged distribution of irrigation water requirement estimated on I0 exp is shown in Fig. 7. A large amount of irrigation water requirement is estimated especially in west part of America, east part of China, north part of India and around the Mediterranean sea.

Fig. 8 and Fig. 9 show 10 years averaged annual cycle of soil wetness at root zone, irrigation water requirement, precipitation and evaporation. It can be seen from these figures that soil wetness and evaporation can be increased by irrigation. As a result, if irrigation effect is considered, that is to say using the

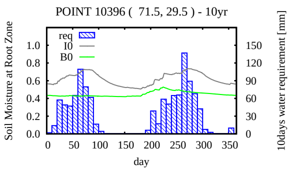


Soil wetness at root zone and irrigation water requiremnent

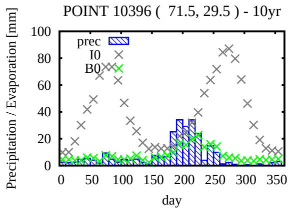


Precipitation and evaporation

Fig. 8 10 years averaged annual cycle of hydrorogical variables at the point SNG (98.5W, 41.5N). The left axis means day of year and the vertical axis means hydrological value. Green line or mark shows the value estimated by B0 exp and black one shows the value of I0 exp.



Soil wetness at root zone and irrigation water requiremnent



Precipitation and evaporation

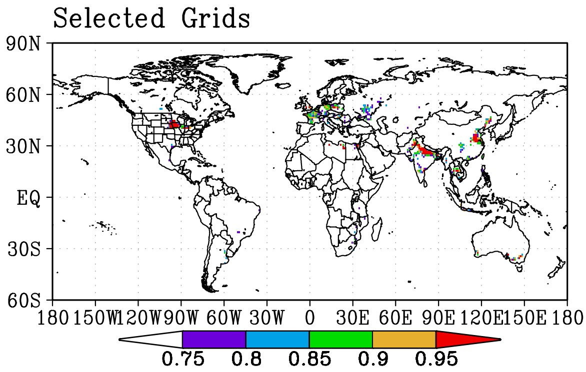
Fig. 9 10 years averaged annual cycle of hydrorogical variables at the point DBL (71.5E, 29.5N). The left axis means day of year and the vertical axis means hydrological value. Green line or mark shows the value estimated by B0 exp and black one shows the value of I0 exp.

model being able to express the artificial water control, evaporation sometimes exceeds precipitation, as is mentioned by Yorozu et al.(2005). This feature is realistic for the area where there is a necessity of the irrigation.

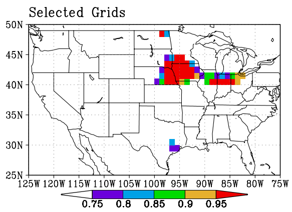
4. Correlation analysis

4.1 Target regions

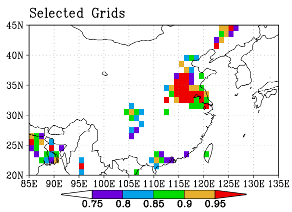
According to a simple analysis for inter-annual variability of precipitation and irrigation water requirement, there seems to be an obvious negative correlation between precipitation and irrigation water requirement. Irrigation water requirement is amount of water that must be applied to achieve optimal crop growth (discussed Sec2.3). So, this water must increase because of less precipitation and must decrease because of much precipitation. Thus, irrigation water requirement should tend to have a negative correlation with precipitation. Therefore, the performance of irrigation scheme is thought to be reasonable.



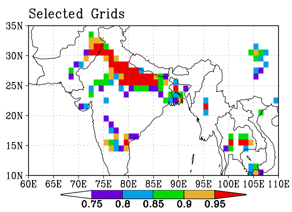
(a) Global distribution



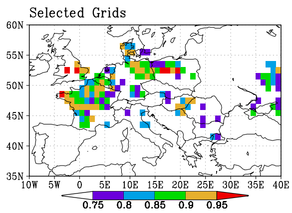
(b) Northern America



(c) East Asia



(d) India region



(e) Europe region

Fig. 10 The global distribution of ratio of cropland to total vegetation.

In order to see model output detail, some grids are selected for analysis. In those grids, the fraction of cropland (both farmland and rice paddy field) is more than 75% of total vegetation area (crop + natural), growing period of crops is more than 30days and irrigation water requirement is calculated.

As a result, 498 grids are selected (see Fig. 10). To assure statistical significance, these grids are aggregated for nation unit or sub-nation unit. Finally, 50 regions remain for detail analysis.

4.2 Precipitation and Irrigation Water Requirement

The correlation coefficient between precipitation and irrigation water requirement is calculated. Categorizing this relationship with levels of statistical signif-

Table 2 Classification by Spearman's correlation coefficient by ranks between precipitation and irrigation water requirement on 50 regions.

correlation	negative	neutral	positive
region number	30	16	4

Table 3 Classification on 50 regions by 2 correlation coefficient, between precipitation and irrigation water requirement (CC1) and between precipitation and NDVI (CC2).

		CC2		
		negative	neutral	positive
CC1	negative	3	**14**	13
	neutral	0	12	4
	positive	1	0	**3**

icance, the number of regions within each category is summarized in Table 2.

As mentioned above, most of regions have negative correlation. However, some regions have positive correlation. What does the positive correlation mean?

In the numerical simulation, irrigation water requirement is calculated without considering the irrigation capacity, for examples, where the water is introduced? or how amount of water can be introduced? In this sense, the calculated irrigation water requirement is a "potential" irrigation amount.

On the other hand, irrigation water requirement is calculated based on the reduction of soil wetness at root zone by transpiration loss from active leaves. This transpiration loss is highly dependent on the amount of active leaves (evaluated by LAI: Leaf Area Index, or NDVI). NDVI data used for estimating LAI are satellite observed product. In other words, NDVI represents the status of crops and other vegetation for each target year. In this sense, the calculated irrigation water requirement is thought to represent "quasi-actual" irrigation amount for each target year.

4.3 Precipitation and NDVI

To understand the different relationship between precipitation and irrigation water requirement, correlation coefficient between precipitation and NDVI is also calculated. In this paper, the former correlation coefficient is called as CC1 (for irrigation water requirement), and the latter is called as CC2 (for NDVI).

Using two correlation coefficient, targeted regions are categorized with threshold levels of statistical significance, the number of regions within each category is summarized in Table 3. Among the regions which have negative correlation with irrigation, nearly half of regions have neutral correlation with NDVI (here, these regions are referred to as type A). This means that the inter-annual variability of NDVI is not determined mainly by precipitation at type A regions.

On the other hand, among the regions which have positive correlation with irrigation, almost all regions have positive correlation with NDVI (here, these regions are referred to as type B). This means that the inter-annual variability of NDVI is strongly dependent on precipitation at type B regions.

4.4 Whether irrigation facilities are adequate

Reconsidering the result of Table 3 in terms of irrigation capacity, type A regions are thought to have enough irrigation capacity. The effect of precipitation variability (especially less precipitation) can be compensated by adequate irrigation water. Owing to this enough irrigation capacity, soil wetness is maintained in appropriate range for optimal growth of crops, and as a result, NDVI is less affected by precipitation variability.

While, type B regions are thought to have inadequate irrigation capacity. The effect of precipitation variability (especially less precipitation) cannot be compensated by limited irrigation water. Because of the limited irrigation capacity, soil wetness sometimes drops down to lower limit for optimal growth of crops, and as a result, NDVI is directly affected by precipitation variability.

Assuming that annual accumulated NDVI value can represent the food production, the model results can be translated into agricultural productivity. Agricultural productivity is not so much affected by precipitation variability at type A regions. While, it is rather vulnerable at type B regions. It may be affected by extreme drought event at other regions.

5. Conclusion

Using the SiBUC model, global 10-year simulation considering irrigation effect has been implemented, and global distribution of irrigation water requirement has been estimated. From the simulation results, it can be assumed that irrigation effect is an important factor in order to estimate the soil wetness accurately. To conduct a simulation more accurately, it is necessary to re-construct the irrigation dataset from a high temporal and spatial resolution data set.

As a result of the simulations, irrigation water requirement tends to have negative correlation with precipitation in most regions. However, some of regions have positive correlation. This different relationship can be explained by the relationship between precipitation and NDVI. Moreover, it can be pointed out where agricultural productivity is resistant to precipitation variability or is vulnerable to precipitation variability. The condition for stability of the agricultural productivity also can be implied from the analysis of both outputs from the land surface scheme and satellite remote sensing data set. From the viewpoint of surface energy and water balance, it is important to express the differences cultivated crop types and the irrigation capacity.

Acknowledgements

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灌漑要求水量 (IWR)・降水量・NDVI の年々変動に関する相関分析

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要 旨

灌漑の効果を考慮できる陸面過程モデル SiBUC (Simple Biosphere including Urban Canopy) を用いて全球土壌水分プロジェクトに参加し，全球陸面水文諸量の算出を行った。得られた陸面再解析データから，灌漑要求水量と降水量，NDVI と降水量の相関分析をそれぞれ行った。その結果，2 つの相関分析の結果を合わせると，灌漑能力に関する情報を抽出しうることが明らかとなった。

キーワード： SiBUC, 相関分析，灌漑要求水量，降水量，NDVI